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Mode-locked Photonic Integrated Circuits for Millimeter and Terahertz Wave Wireless Communications

Mu-Chieh Lo, Robinson Guzmán, Carlos Diego Gordón, Guillermo Carpintero

Universidad Carlos III de Madrid, Av de la Universidad, 30. 28911 Leganes. Madrid. Spain.

Abstract- We present a 160 GHz pulsed source, based on an on-chip repetition rate multiplier scheme to double the repetition rate of an 80 GHz multiple pulse colliding mode-locked (mCPM) laser. For the first time to our knowledge, we demonstrate the monolithic integration of the mCPM laser and the pulse rate multiplier structures, using a generic foundry approach. From a 20 GHz fundamental repetition rate we achieve a x4 increase, up to 160 GHz. The FWHM pulsewidth of 160 GHz pulse train is 2.77 ps.

I. Introduction

Recent trends show that the demand for increasing the wireless communication data rates is growing explosively in conjunction with the continuous increase in the memory size on mobile devices [1]. Another factor that will push the demand for wireless speed is the new TV standards resolution increase, as the 4KUltra-High Definition (also known as UHD) has four times as much detail as 1080p Full HD. Streaming of 4K UHD signal requires an enormous amount of bandwidth, roughly about 24 Gbps. NHK, the Japanese state owned broadcasting company, is aiming to shoot and transmit the 2020 Tokyo Olympics in the format 8K UHD (doubling the 4K definition to 33 million pixels). To reach the wireless data rates that are expected to be needed by 2020, wireless speeds need to be pushed up 100 Gbit/s.

For such ultra-high speed wireless links, researchers have been seeking the exploit of millimeter- (mmW, 30 GHz to 300 GHz) and Terahertz- (THz, 300 GHz to 3 THz) range of the frequency spectrum [2]. The difficulty to access this frequency region, commonly referred to as the THz gap, has maintained this region free. Now it is seen as vast region for available bandwidth.

The generation, amplification, and modulation of electronic signals are difficult because the characteristics of semiconductor devices deteriorate as the frequency increases. For this reason, photonic-based technologies have been pioneering the access to this spectral range, and additionally providing numerous advantages over electronic-approaches [3]. While the most notable advantages are the quality of the generated signal and the maximum generated frequency (up to 3 THz), photonics also offers a wide data modulation bandwidth as well as bringing the possibility to achieve a seamless integration of existing wired fiber-optic systems with broadband wireless.

There are various photonic techniques to generate MMW and THz frequencies, among which optical heterodyning and pulsed techniques are commonly used. Pulsed sources are usually based on mode locked laser (MLL) structures [3], having recently reported that it can increase the radiated emitted power about 7 dBm above heterodyning schemes [4]. One of the main issues in order to increase the MLL repetition rate frequency into the multi-GHz range is that this frequency is inversely proportional to the cavity length. A 300 GHz repetition rate frequency would require a 133 μm long cavity, too small to provide any significant amount of optical power. Thus schemes to increase the repetition rate without decreasing the cavity length must be addressed.

We have recently reported on-chip multiple colliding pulse mode-locked (oc-mCPM) semiconductor laser structures, fully integrated on a chip through used of multimode interference reflectors (MIRs). The multiple colliding regime is key to generate a repetition rate at a multiple of the fundamental round-trip frequency, demonstrating a repetition rate within the millimeter wave frequency range, at 100 GHz using a 25 GHz PIC-based mode-locked (ML) semiconductor laser [5].

In this paper, we demonstrate a novel type of MLL structure in which we combine on-chip a multiple colliding pulse mode-locked (oc-mCPM) together with a repetition rate multiplier based on optical time-division multiplexing as shown in Figure 1. This is the first time that the optical millimeter wave generator structure used in is monolithically integrated [6], pushing the generated frequency from 120 GHz up to 300 GHz. It is worth to highlight that the proposed structure that we demonstrate is developed as a Photonic Integrated Circuit (PIC), which addresses the two most important concerns of photonic-based approaches, which are cost and size [7]. While the size is addressed through integration of multiple functional blocks on the same chip, using generic photonic integration platforms allows to address the cost issue. Generic integration reduces the cost by using design tools, which employ standardized photonic component building blocks (BBs) with known performance, based on a fix fabrication process flow, fabricated in a Multi-Project Wafer (MPW) run [8].

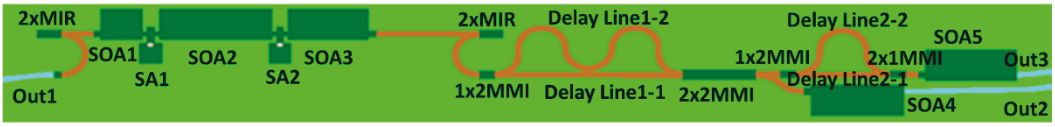

Figure 1 on-chip multiple colliding pulse mode-locked with repetition rate multiplier

II. Device Description

A. Multiple colliding pulse mode-locked

The repetition rate frequency of the laser depends on the length of the resonator cavity and the number of pulses propagating through it. In addition, high repetition rates cannot be achieved through short cavity lengths, since there is a minimum gain necessary to overcome the cavity losses. To realize a repetition rate of 80 GHz with a longer cavity (that corresponds to 20 GHz) we use multiple colliding-pulse (mCPM) mode-locking techniques, featuring several saturable absorbers (SAs) and semiconductor optical amplifiers (SOAs), with precise locations along the cavity as shown in **Figure 2**.

Figure 2 multiple colliding pulse mode-locked. SOA: semiconductor optical amplifier, SA: saturable absorber, 2xMIR: 2 ports multimode interference reflector

The total cavity length is about 2 mm, defined by a pair of 2-port MIRs (2xMIRs), providing 50% reflectivity. The fundamental repetition rate is therefore 20 GHz. At the center of the cavity, we place the saturable absorber SA2, which is nothing else than a 30 um reversed-biased SOA. The at the center of one of the halves defined by SA1, we place a second SA (SA1), at ¼ of the total cavity length. This allows us to increase the number of pulses in the cavity to four, increasing the repetition rate to 20 GHz x 4 = 80 GHz. Three SOAs of different lengths are distributed along the cavity to provide optical gain. All these active sections are all based on the same InGaAsP multi-quantum well core. The chip, fabricated in an active-passive integration technology allows us to use passive waveguides to maintain the optimum SOA to SA length ration of 20:1.

The use of 2xMIR mirrors allows us to have the optical pulse train on chip for further optical signal processing of the signal, to increase the repetition rate.

B. repetition rate multiplier

In order to increase the repetition rate to a higher harmonic, we use an optical clock multiplier, to increase it to 160 GHz and 320 GHz. The on-chip multiplier is shown in **Figure 3**, which uses a pulse inter-leaver structure, which splits the pulse train in two, and propagates each along two different paths, one of which is delayed prior to their recombination. As shown we used an MMI splitter, two passive waveguide routes with different path length (providing time delay control with the lithographic accuracy), and another MMI as combiner. By using the delay line-assisted Mach Zehnder interleaver, the repetition rate of original pulse train is doubled.

Delay Line 1-1 is a straight waveguide of 800 um while Delay Line 1-2 is a combination of curved waveguide of 1330 um. Similarly, for the second stage of interleaver Delay Line 2-1 is 400 um with Delay Line 2-2 being 796 um long. The signal processed via Delay Line 1 and Delay Line 2 travels into SOA5. The other one that has gone through Delay Line 1 enters SOA4. Hence a processed pulse train with a repetition rate of 320 GHz is achieved after SOA5 and the other one of 160 GHz is achieved after SOA4. These two SOAs as booster are deployed before waveguide outputs. This circuit includes five SOAs, two SAs, two MIRs, several MMIs as well as passive components. The laser is fabricated in a multiproject wafer (MPW) run by Smart Photonics InP foundry, through JePPIX which is a European platform for photonic integrated circuits (PIC).

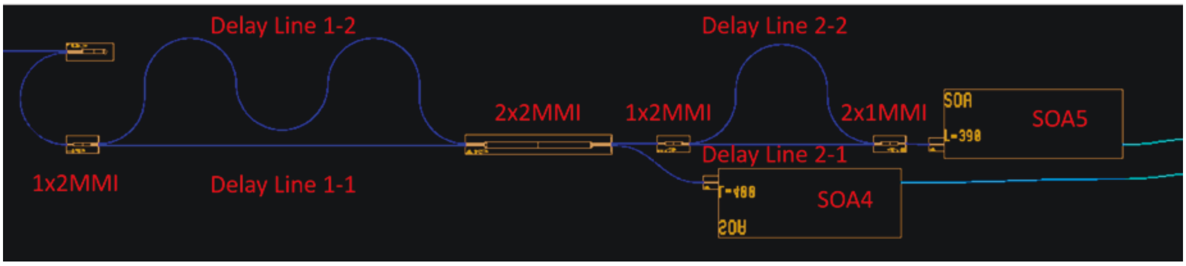

Figure 3 repetition rate multiplier based on optical time-division multiplexing. MMI: multimode intereference coupler.

III. Results

In order to demonstrate the optical pulse multiplication, we have measured the optical spectrum from the chip at the different output waveguides on a Yokogawa AQ6370B optical spectrum analyzer (OSA). As presented in **Figure 4**, two spectra of 80 GHz and 160 GHz stand side by side within the same span of 1546 - 1552 nm. The left is a typical multiple pulse colliding mode locked spectrum of 80 GHz with its fundamental frequency of 20 GHz. It shows five - seven obviously higher peaks which the spectral spacing in between is 0.652 nm corresponding to 81.5 GHz while the spacing between adjacent lower peaks is 0.164 nm corresponding to about 20.5 GHz. The side mode suppression ratio is around 30 dB. The right of Figure 4 is the spectrum of 160 GHz pulse train signal, measured at Out2 in Figure 1. Compared to the 80 GHz spectrum, every one out of two 80 GHz peaks is suppressed in the spectrum of 160 GHz. The spacing between longest peaks is 1.308 nm and the power ratio between 160 GHz and 80 GHz peak is 20 dB. The 160 GHz spectrum has a wavy baseline which is caused by the interference between delay line arms. And the Mach Zehnder structure act as a pass band filter with its band being equivalent to the 160 GHz spectral spacing. This effect improves side mode suppression ratio by around 5 dB.

In Figure 5, two second harmonic generation autocorrelations of the identical signal (the 160 GHz pulse train) are plotted with span of ±2.5 ps and ±25 ps, respectively. They are measured using APE pulse check autocorrelator at Out2 in Figure 1. Referred to Figure 1Figure 5 (Left), the full width at half maximum is 2.77 ps and as illustrated in Figure 5 (Right), the time displacement between each pulse is around 6.06 ps, equal to 165 GHz . Also it shows an unflattened envelop of pulse train, which may be caused by imperfection of design.

IV. Conclusion

We have developed a pulsed source of 160 GHz comprising an 80 GHz multiple pulse colliding mode locked laser with 20 GHz fundamental frequency, and a delay-line-assisted Mach Zehnder interleaver as x2 rate multiplier. The spectrum of mode locked laser output both with repetition rate multiplier have shown that the side mode suppression ratio is 20 dB which has been affected positively by Mach Zehnder interferometer. And the SHG autocorrelations of 160 GHz signal over a span of 5 ps and 50 ps are plotted to characterize the pulse and pulse train. The pulsewidth is 2.77 ps. In contrast to the design expectation, the experimental repetition rate has a 5 GHz error.

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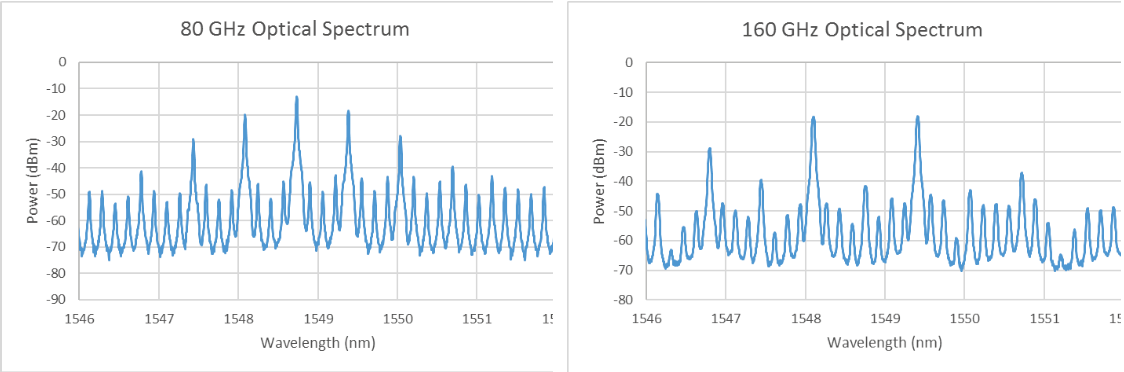

Figure 4 (Left) optical spectrum from the 80 GHz mCPM laser optical output, (Right) optical spectrum of 160 GHz optical output (2x multiplier output).

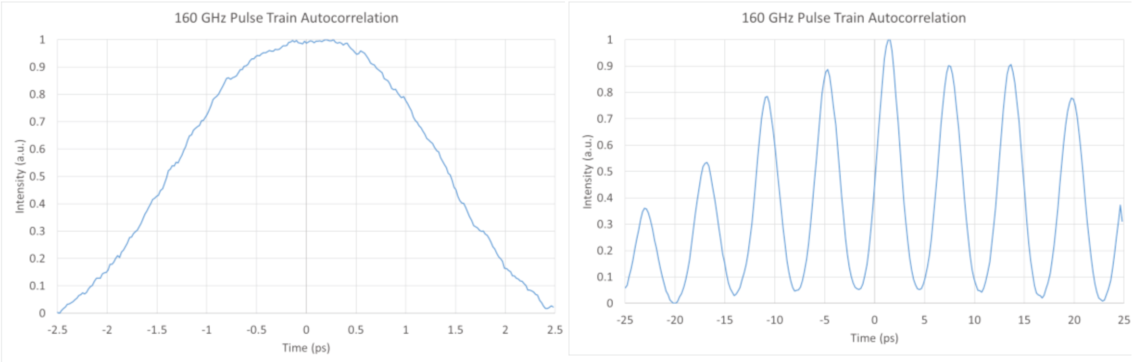

Figure 5 (Left) Autocorrelation of 160 GHz pulse train, span: 5 ps. (Right) Autocorrelation of 160 GHz pulse train, span: 50 ps.

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